Is the Universe Unreal as per Quantum Mechanics?*

Jayanth Vyasanakere

The announcement of the 2022 Nobel Prize in Physics to A. Aspect, J. F. Clauser and A. Zeilinger, with the citation "*for experiments with entangled photons, establishing the violation of Bell's inequalities and pioneering quantum information science*," has rekindled an old debate—*is the universe real, or is it just our imagination*? Social media is exploding with statements like quantum mechanics (QM) has proved that the "universe is not real", "reality is an illusion", "it is all our mind's projection", "objects exist only in our heads", "nothing exists out there", "conscious observer brings the world into existence", and so on... Anyone who has worked on quantum systems or has taught QM would find such statements superficial, misrepresenting QM and even the process of science. So, what QM advocates in connection to reality is critically examined here.

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Background

Quantum mechanics (QM), developed during the early 20th century, is outstanding in explaining and predicting various phenomena, extending from subatomic to astronomical scales, that cannot be captured within the classical (Newtonian) framework. QM also reduces itself to the latter in the right limit to restore its accomplishments. QM continues to be an exceedingly successful theory even today and is the backbone of most of the technology we are using. For example, it is impossible to explain why some materials are metallic and some are not without QM.

While the mathematical algorithm of QM has always been crystal clear, it is nontrivial to give it a physical picture. A desperate

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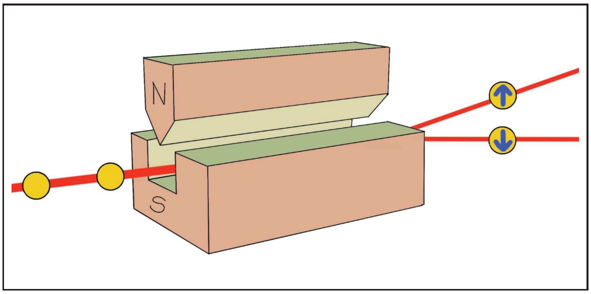

Figure 1. A schematic of the Stern–Gerlach experiment. Silver atoms (yellow spheres) travel from left to right, go through a region of spatially varying magnetic field (between the magnets shown as N and S), and get deflected either up or down depending on the spin-state (blue arrows) they collapse to.

search for a classical explanation of a quantum theory is the central source of unease. In that process, the technical terminology gets abused, often resulting in the misinterpretation of scientific discoveries to fit one's favorite philosophy. As Richard Feynman remarked [1]—"When philosophical ideas associated with science are dragged into another field, they are usually completely distorted." Therefore, let's take a concrete example and break the ideas of QM into simpler digestible pieces.

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Basics of Quantum Mechanics

Consider the historic Stern–Gerlach (SG) experiment schematically depicted in *Figure* 1. Here a beam of silver atoms, upon passing through a specific arrangement of magnets, gets split into two discrete beams.

There is no classical explanation for this observation. In QM, the particles have an attribute called 'spin', and in this case, the spin of the silver atom can be shown to have only two possible values—'up' and 'down'. It then follows, from more physics, that the atoms having their spin 'up' will feel an upward force within the magnetic field (or a downward force, depending on the sign of the field gradient) and hence travel upwards (or downwards). Similarly, those having their spin 'down' will end up moving downwards (or upwards).

While this explains the splitting of the beams, it raises a fundamental question: For a given atom, before the split, can we predict whether it is going to go up or down? In other words, can we say for sure what is the spin of the atom in question, before it goes through the magnetic field? The answer in QM is a "no" in general! All one can talk about and calculate is what is called the 'wave function' or 'state' of an atom. This can only provide the probability of the atom taking one path or the other. For example, if you take 100 atoms with the same wave function, you can tell some 70 of them, or some such number, depending on the wave function, would go up, and the remaining would go down. One cannot predict, with certainty, what the fate of a particular atom would be. This is similar to the coin toss experiment, where one can talk about the probability of getting heads/tails when the coin is tossed but can never predict the precise outcome in a particular trial.

The process of 'an atom going through the magnetic field' counts as an observation or a measurement. That is the point after which you can assign, with certainty, a specific spin (up or down) to the atom. In technical jargon, the wave function of the atom 'collapses' to the spin-up or the spin-down state upon measurement.

The Different Schools of Thought

The main philosophical debate here was regarding the uncertainty that exists before a measurement. Three schools of thought attempted to dig deeper [2].

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The first one, called the realist school of thought led by Albert Einstein, essentially said that QM being an approximate theory, could only deal with probabilities. A more complete theory, called the 'hidden variable' theory, which may perhaps get discovered in future, should be able to give more information than what the wave function in QM could do, so that the precise outcome, i.e., spin up or spin down, can be predicted for every single atom.

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The second, called the orthodox school of thought, led by Niels Bohr, Heisenberg, and others, argued that it was the measurement that forced the atom to assume an up or down spin state, before which the wave function is the best possible description. Within their stand, the uncertainty before the measurement and the collapse of the wave function during the measurement are very much part of nature.

The third, the agnostic school of thought, believed that this debate can never get settled. They continued using QM to calculate and understand more and more of nature without getting bogged down by its conceptual foundations.

How was the Debate Settled?

In 1964, John Bell came up with a brilliant set of arguments [3]. He showed that if the universe is described by a more complete theory and therefore deterministic as advocated by the realist school of thought, then within a particular class of experiments involving two particles, a set of inequalities (called Bell's inequalities) have to be necessarily valid, as long as 'locality' (that influences cannot travel faster than light) is respected. The fact that these inequalities will have to be obeyed irrespective of the detailed nature of the 'hidden variables' that would occur in that more complete theory, allowed the debate to proceed without explicitly having such a theory in hand.

Setting aside the agnostic school, the philosophical debate then reduced to an experimental question—whether Bell's inequalities were respected or not in the appropriate class of experiments. The Nobel laureates performed masterful experiments [4–6] to conclusively show that Bell's inequalities are actually violated! This then settled the debate, ruling out the realist school of thought. This means that QM is not an incomplete theory, and the description of the atom in terms of its wave function and associated probabilities is all that is there before the measurement, in accordance with the orthodox interpretation.

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Earlier, in 1935, Einstein, Podolsky, and Rosen (EPR) had argued that the orthodox interpretation is not viable as it violates the principle of causality (that an effect cannot occur before its cause) in certain systems [7]. It was later correctly interpreted as only a violation of locality but still preserving causality. The details around locality are not discussed here as they are not directly related to this discussion. The idea is very similar to what happens in the lighthouse effect [8], where a bright spot or even shadow can be made to travel faster than light without violating the theory of relativity.

What do all These Mean for 'Reality'?

'Reality' in QM has a completely different connotation and simply does not correspond to the colloquial meaning of the word.

With all these concepts dissected, it is obvious that 'reality' in QM has a completely different connotation and simply does not correspond to the colloquial meaning of the word. In QM, realism basically refers to the existence of a more complete theory that can predict the physical quantities without uncertainty, and to which QM itself is an approximation. Proclaiming that the world is our illusion just based on the word 'real' is as ridiculous as saying that QM supports traditional or conservative views because the experimental verdict is in favor of the 'orthodox' school of thought! Even in mathematics, complex numbers, which are not necessarily 'real' (in yet another sense), are not anyone's illusion.

Let us now audit the situation by revisiting the SG experiment and see explicitly if there is any scope for illusion.

Before the measurement, we know everything about the atom. That is the state of the particle or its wave function. Was that really the wave function? Yes, it was. Did it give the right probabilities? Yes, definitely. Did we miss anything about the situation at all? No, we didn't; wave function is all that is there about the atom, which is precisely the point that won the Nobel Prize. At any point of time, will we have a realization that our knowledge of the atom in any way was wrong and that what existed was something else? No, never. This is then the litmus test to conclude that one had no illusion about the atom before the measurement.

How about the situation soon after the measurement? Whether you observe the atom or choose not to, it doesn't matter; you can say, with full confidence, even the value of the physical quantity measured. This is why repeated measurements always produce consistent outcomes. In more concrete terms, if you take the beam that has gone up in the SG experiment, you know for sure that the spins of those atoms are 'up'. As a result, subsequent measurements of the spin will consistently return the value as up, i.e., if you channel them to go through a similar magnetic setup, they will all again go up. So, the spin of the particle in such quantum states is 'real', even in the physicists' sense of the word.

A measurement can only alter the state of a system, but it does not create one from nowhere!

Does the process of measurement change the state of the system? Yes. Does it mean there was an illusion? No. This is the key point to understand. A measurement can only *alter* the state of a system, but it does not *create* one from nowhere! The atom always exists, both before and after the measurement; it's just that its state changed due to the measurement. We precisely knew the state in which the atom truly existed before the measurement; we precisely know the true state to which it collapsed. When you are interfering with the system (using magnets, for example), that the state of the system changes is also, of course, expected.

Can we predict *how* the measurement changes the state of the system? No, not precisely; but we can list out all the possible ways in which the state can change and even find out the associated probabilities. Is the process of measurement completely well understood? No, there are a few theories around the measurement problem waiting for decisive experimental confirmation. But do these mean there was an illusion? Again no. We are aware of an innumerable bunch of things that are not in our hands and those which are yet to be explored. But that has nothing to do with illusion; they only reflect our limitations.

The observer in QM does not necessarily refer to a living being. It can be a photographic plate, a camera, or just a pair of magnets, as in the SG experiment.

It is also crucial to note that the collapse of the wave function is definitely not governed by what is in our heads! Furthermore, the observer in QM does not necessarily refer to a living being. It can be a photographic plate, a camera, or just a pair of magnets, as in the SG experiment. Accordingly, appealing to '*consciousness*' here is incorrect.

After all, the results of the experiments by the Nobel laureates, on which this entire discussion is based, were *observed* by them, and we do seriously believe that those observations were real and not their illusion!

Conclusion

While QM has a strong say in our transactions with the reality that exists out there, there is no question of the universe being ‘unreal’ in the colloquial sense of the word. Thus, the universe is indeed real, and the fact that QM has brought real technological applications has only made the world around us more real than ever before.

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Suggested Reading

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